

# Constraints on the large- $x$ $d/u$ ratio from electron–nucleus scattering at $x > 1$

O. Hen,<sup>1</sup> A. Accardi,<sup>2,3</sup> W. Melnitchouk,<sup>3</sup> and E. Piasetzky<sup>1</sup>

<sup>1</sup>*Tel Aviv University, Tel Aviv 69978, Israel*

<sup>2</sup>*Hampton University, Hampton, Virginia 23668, USA*

<sup>3</sup>*Jefferson Lab, Newport News, Virginia 23606, USA*

Recently the ratio of neutron to proton structure functions  $F_2^n/F_2^p$  was extracted from a phenomenological correlation between the strength of the nuclear EMC effect and inclusive electron–nucleus cross section ratios at  $x > 1$ . Within conventional models of nuclear smearing, this “in-medium correction” (IMC) extraction constrains the size of nuclear effects in the deuteron structure functions, from which the neutron structure function  $F_2^n$  is usually extracted. The IMC data determine the resulting proton  $d/u$  quark distribution ratio, extrapolated to  $x = 1$ , to be  $0.23 \pm 0.09$  with a 90% confidence level. This is well below the SU(6) symmetry limit of  $1/2$  and significantly above the scalar diquark dominance limit of 0.

## I. INTRODUCTION

Currently uncertainties in parton distribution functions (PDFs) at large parton momentum fractions  $x$  represent one of the main impediments to the determination of the longitudinal structure of the nucleon in terms of its fundamental constituents. The large- $x$  region provides a unique opportunity for studying the flavor and spin dynamics of quarks in the nucleon, with the  $d/u$  quark distribution ratio in particular being very sensitive to different mechanisms of spin-flavor symmetry breaking [1, 2]. Knowledge of PDFs at large  $x$  is important also for several other reasons, such as the reliable calculation of QCD backgrounds in new physics searches at hadron colliders, especially at large rapidities, as well as in neutrino oscillation experiments.

The systematics of uncertainties in parton distributions at large  $x$  has been the focus of recent dedicated global QCD analyses by the CTEQ-Jefferson Lab (CJ) Collaboration [3, 4], which investigated the sensitivity of PDFs to different treatments of nuclear corrections in deep-inelastic scattering (DIS) from deuterium. While proton DIS data place strong constraints on the  $u$ -quark distribution, neutron structure functions are needed in order to determine also the  $d$ -quark PDF. The absence of free neutron targets, however, means that deuterium DIS data must be used to infer information about the structure of the free neutron.

Uncertainties in the nuclear corrections in the deuteron, such as those associated with nucleon off-shell effects and the large-momentum components of the deuteron wave function, give rise to significant uncertainties in the resulting  $d/u$  ratio for  $x \gtrsim 0.5$  [4]. This prevents drawing any firm conclusions about the  $x \rightarrow 1$  behavior of  $d/u$  predicted in various nonperturbative and perturbative models, which range from 0 in models with scalar diquark dominance [5–7] to  $\approx 0.2$  in models with admixtures of axial-vector diquarks [8] or those based on helicity conservation [9], and up to 0.5 in models with SU(6) spin-flavor symmetry [10].

A recent analysis of the strength of the EMC effect in nuclei and data on inclusive electron–nucleus scat-

tering at  $x > 1$  proposed a phenomenological, theory-independent, determination of the neutron to proton structure function ratio  $F_2^n/F_2^p$ , known as the “in-medium correction” (IMC) extraction [11]. The IMC analysis is based on the observed correlation between the strength of the nuclear EMC effect at intermediate  $x$  ( $x \approx 0.3 - 0.7$ ) and the number of short range correlated nucleon–nucleon pairs in light, medium, and heavy nuclei, which is then extrapolated to a free nucleon.

In this report we combine the phenomenology of these two approaches, and illustrate how the IMC extracted neutron structure function can in principle limit the range of parameters describing nuclear corrections in the deuteron, thereby significantly reducing the uncertainties in the resulting  $d/u$  ratio at large  $x$ . As we shall see, the IMC analysis favors values of  $d/u$  at the upper end of the uncertainty band obtained in the CJ global QCD fit [4], indicating the presence of significant nucleon off-shell corrections in the deuteron structure function.

## II. NUCLEAR EFFECTS IN THE DEUTERON

In the conventional description of DIS from the deuteron at  $x \gg 0$ , the scattering is assumed to take place incoherently from individual nucleons in the deuterium nucleus [12]. In the weak binding approximation (WBA), the deuteron structure function can be written as a convolution of the bound nucleon structure functions  $F_2^N$  and a momentum distribution function of nucleons in the deuteron (also known as the “smearing function”) [13–15].

In Ref. [14], Kulagin and Petti used a simple quark spectral model to obtain a physically motivated parametrization of the nucleon off-shell corrections (see also Refs. [13, 16–18]). The off-shell corrections were estimated by integrating the quark–nucleon spectral function over quark virtualities up to some high-momentum scale  $\Lambda$  that depends on the nucleon off-shell mass  $p^2 = p_0^2 - \mathbf{p}^2 \neq M^2$ , where  $p_0 = M_d - \sqrt{M^2 + \mathbf{p}^2}$  is the nucleon energy and  $\mathbf{p}$  its momentum, with  $M$  and  $M_d$  the nucleon and deuteron masses. Taking  $\Lambda$  to be inversely propor-

tional to the quark confinement radius  $R$  in the nucleon, its dependence on  $p^2$  can be related to the change in the size of the nucleon in the nuclear medium (“nucleon swelling”). The change of scale  $\delta R$  and nucleon virtuality can be conveniently parametrized in terms of a single parameter  $\lambda$ , given by [14]

$$\lambda = \left. \frac{\partial \Lambda^2}{\partial \log p^2} \right|_{p^2=M^2} = -2 \frac{\delta R}{R} \frac{\delta p^2}{M^2}, \quad (1)$$

where  $\delta p^2$  is the average nucleon virtuality ( $p^2 - M^2$ ) in the deuteron.

The parameter  $\lambda$  was chosen in Ref. [4] to reproduce the phenomenological values of the change of confinement radius from the study of the nuclear EMC effect in the  $Q^2$ -rescaling model [19],  $\delta R/R = 1.5\% - 1.8\%$ . This was somewhat smaller than the nuclear-averaged value of  $\delta R/R \approx 9\%$  obtained by fitting the off-shell correction to ratios of nuclear structure functions for a range of nuclei [14]. While it is generally accepted that some off-shell corrections to the convolution approximation are needed in order to describe nuclear structure functions at large  $x$  [20], their magnitude varies considerably between different models [14, 17, 18, 21–23], and on the definition of the smearing function. (In fact, in some approaches such as the light-front [24–26] explicit off-mass-shell corrections do not appear at all, their effects instead being subsumed by higher Fock state components or contact interactions.)

In the present analysis we treat  $\lambda$  as a free parameter, allowing it to be determined by the IMC extraction data for a given virtuality  $\delta p^2$ . The latter is computed from several modern deuteron wave functions which give high-precision fits to nucleon-nucleon scattering data, namely, the CD-Bonn [27], AV18 [28], and the relativistic WJC-1 and WJC-2 wave functions [29], yielding values of the nucleon virtuality of  $\delta p^2/M^2 = -3.7\%, -4.5\%, -6.2\%$  and  $-4.9\%$ , respectively. (The older Paris deuteron wave function [30] gives a value  $\delta p^2/M^2 = -4.3\%$ , similar to the AV18 model.) This “modified Kulagin-Petti” (mKP) parametrization of the off-shell corrections (1) allows a wide range of models to be assessed in terms of a single parameter, the nucleon swelling  $\delta R/R$ , for a given deuteron wave function.

### III. IMC CONSTRAINTS ON THE $d/u$ RATIO

In Fig. 1 the ratio of neutron to proton structure functions  $F_2^n/F_2^p$  at  $Q^2 = 12 \text{ GeV}^2$  is shown for various deuteron wave functions and swelling levels  $\delta R/R$ , ranging from 0% to 3%, in increments of 0.3%, using the WBA smearing function and the mKP off-shell model. For each combination of wave function and swelling parameters, the structure functions are computed from the CJ global next-to-leading order QCD fit of PDFs as described in Ref. [4], using a flexible parametrization for the  $d$ -quark PDF which allows finite  $d/u$  values as  $x \rightarrow 1$ . Each of the

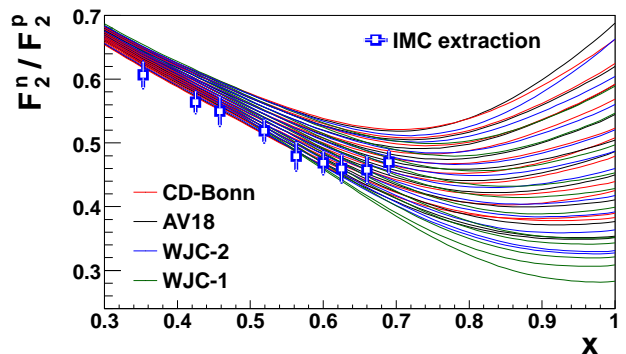


FIG. 1: Neutron to proton structure function ratio  $F_2^n/F_2^p$  from the CJ global QCD fit [4] assuming different deuteron wave functions: CD-Bonn (red), AV18 (black), WJC-1 (green) and WJC-2 (blue). The curves correspond to different nucleon swelling levels,  $\delta R/R$ , ranging from 0% (lowest curves) to 3% (highest curves) in steps of 0.3%. The IMC data (squares) [11] and the fits are at a fixed  $Q^2 = 12 \text{ GeV}^2$ .

fitted PDF sets represented by the curves in Fig. 1 gives a similar quality fit to the global data base used in Ref. [4], by allowing the changes in the nuclear corrections to the deuteron  $F_2^d$  structure function to be compensated by corresponding changes in the  $d$ -quark PDF (inducing a similar change in the calculated neutron  $F_2^n$ ). The curves are compared with the  $F_2^n/F_2^p$  ratios obtained from the IMC extraction over the range  $0.35 \lesssim x \lesssim 0.7$ .

To constrain the nuclear correction uncertainty in  $F_2^n/F_2^p$ , we calculate the  $\chi^2$  of the IMC data for each deuteron wave function and swelling combination. This is shown in Fig. 2 (left) as a function of the nucleon swelling  $\delta R/R$  for the different deuteron wave functions. Note that the wave function determines not only the average nucleon virtuality  $\delta p^2$  in the deuteron, but also the amount of binding and Fermi motion in the smearing function [4, 15]. For the choice of confidence level (C. L.) we treat the deuteron wave function as a (discrete) parameter, and consider a 90% C. L. for two free parameters, corresponding to an increase in  $\chi^2$  of 4.61 above the minimum. With this C. L. the IMC extraction constrains the swelling levels to the range  $\delta R/R = 0.2\% - 1.4\%$ , with a preference for the CD-Bonn, AV18 and WJC-2 wave functions. The minimum  $\chi^2$  occurs for the CD-Bonn model at  $\delta R/R = 0.9\%$ . The minimum  $\chi^2$  for the WJC-1 wave function at  $\delta R/R \approx 1.5\%$  lies outside of the 90% C. L. and is disfavored by the IMC data.

The implications of these constraints for the  $d/u$  ratio in the limit  $x \rightarrow 1$  are illustrated in Fig. 2 (right), where the  $\chi^2$  is shown as a function of the limiting  $d/u$  value of each PDF fit. The IMC extraction yields a  $d/u$  limiting value of  $0.23 \pm 0.09$  at the 90% C. L. (at the 99% C. L., using a  $\chi^2$  increase of 9.21, the uncertainty would increase to  $\pm 0.13$ ). These results strongly disfavor the SU(6) value  $d/u = 1/2$ , as well as the  $d/u \rightarrow 0$  limit predicted in models with scalar diquark dominance. Furthermore, global PDF analyses often assume the same

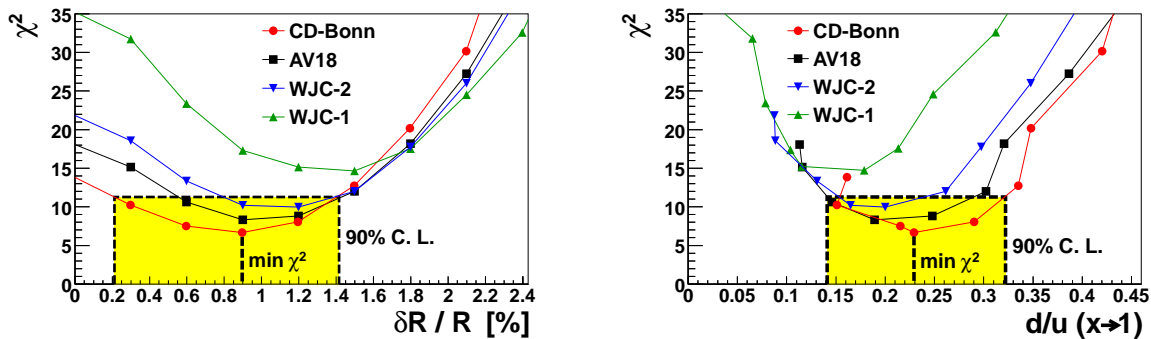


FIG. 2: Total  $\chi^2$  for fits of the calculated  $F_2^n/F_2^p$  ratios in Fig. 1 to the IMC extraction data [11] for various deuteron wave functions (CD-Bonn – circles, AV18 – squares, WJC-2 – inverted triangles, WJC-1 – triangles), as a function of the swelling level  $\delta R/R$  (left), and the  $d/u$  ratio in the  $x \rightarrow 1$  limit (right). The 90% confidence levels are indicated by the shaded (yellow) box, and the minimum  $\chi^2$  values by the vertical dashed line.

functional  $x$  dependence for both  $u$  and  $d$  quark distributions, forcing the  $d/u$  ratio to approach either zero or infinity in the  $x \rightarrow 1$  limit. The results shown in Fig. 2, however, suggest that a more flexible parametrization for the  $d/u$  ratio, which allows finite  $x \rightarrow 1$  limits, may be more realistic [4].

The resulting uncertainty bands on the  $d/u$  ratio are shown in Fig. 3, including the full theoretical uncertainty from the CJ global fit [4], and the 90% C. L. extracted from the IMC constraints. Even though the IMC extraction only covers an  $x$  range of  $\approx 0.35 - 0.7$ , it nevertheless imposes a tight constraint on the  $d/u$  parton distributions ratio for  $x \rightarrow 1$ .

#### IV. SUMMARY

Within a global PDF analysis we have studied the constraints imposed by the theory-independent IMC-extracted  $F_2^n$  structure function data on nuclear corrections in deuterium. These phenomenologically extracted data strongly support the presence of off-shell modifi-

cations of nucleons in the deuteron, and constrain their magnitude to a more limited range than in the recent CJ global QCD analysis without the IMC data [4]. The IMC data also disfavor deuterium wave functions with very “hard” momentum distributions, such as for the WJC-1 nucleon-nucleon potential [29], which produce a shallow EMC ratio  $F_2^d/F_2^N$  at intermediate and large  $x$  [4, 15].

While the  $u$ -quark PDF is well constrained by the proton DIS data, the lack of a free neutron target makes the  $d$ -quark distribution very sensitive to the assumptions used to calculate the nuclear correction in the deuteron. The use of the IMC-extracted neutron structure function directly constrains the  $d$ -quark PDF for  $x \lesssim 0.7$ , and indirectly for  $x \rightarrow 1$ . We find the  $d/u$  ratio in the limit  $x \rightarrow 1$  to be  $0.23 \pm 0.09$  at the 90% confidence level, in agreement with models predicting intermediate values of  $d/u$  between the SU(6) symmetry and scalar diquark dominance limits [8, 9].

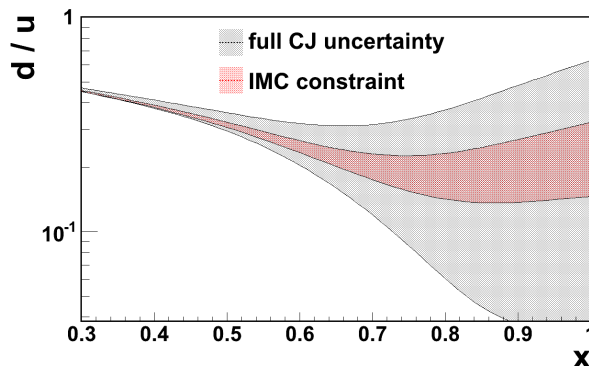


FIG. 3:  $d/u$  ratio at  $Q^2 = 12 \text{ GeV}^2$  with the full theoretical uncertainty from Ref. [4] (black) and with the IMC constraint at the 90% C. L. (red).

Of course, these conclusions strongly depend on the assumptions underlying the IMC extraction of  $F_2^n$  [11]. Some of these are being tested through the study of DIS events with a tagged high-momentum proton recoil at Jefferson Lab [32], and will be the subject of a similar experiment at the future 12 GeV upgraded facility [33]. The ultimate arbiter, however, will be data on free or nearly free neutron targets, such as from the BoNuS experiment [34] at Jefferson Lab that collected DIS data up to  $x \approx 0.6$ , or its future 12 GeV extension [35] that will reach  $x \approx 0.8$ . Further avenues to direct experimental constraints on  $d/u$  at large  $x$  include the 12 GeV MARATHON experiment [36] at Jefferson Lab on DIS from the  $^3\text{He}$ - $^3\text{He}$  mirror nuclei and the parity-violating DIS program on a hydrogen target [37], as well as the measurement of  $W$  boson asymmetries at large rapidities in  $p\bar{p}$  collisions at the Tevatron or in  $pp$  scattering at RHIC and the LHC [4, 38].

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